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USE OF THE LONG DURATION EXPOSURE FACILITY'S THERMAL MEASUREMENT SYSTEM FOR THE VERIFICATION OF THERMAL MODELS

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SUMMARY

The Long Duration Exposure Facility (LDEF) post-flight thermal model predicted temperatures have been matched to flight temperature data recorded by the Thermal Measurement System (THERM), LDEF experiment P0003. Flight temperatures, recorded at intervals of approximately 112 minutes for the first 390 days of LDEF's 2105 day mission were compared with predictions using the thermal mathematical model (TMM) . This model was unverified prior to flight. The post-flight analysis has reduced the thermal model uncertainty at the temperature sensor locations from ±40°F to ±18°F. The improved temperature predictions will be used by the LDEF's principal investigators to calculate improved flight temperatures experienced by 57 experiments located on 86 trays of the facility.

INTRODUCTION

The LDEF THERM experiment was developed to reduce the large uncertainties of ±40°F on predicted boundary temperatures calculated with the pre-flight LDEF thermal mathematical model (TMM). The high uncertainties of the model arise from the large number of complex flight hardware elements being represented by a reduced node TMM and the large number of bolted and clamped joints with uncertain thermal conductance. Due to the LDEF's large size and the logistical problems associated with experiment tray integration, it was impractical to perform a pre-flight thermal test to verify the TMM. A verified LDEF TMM with reduced calculated temperature uncertainties was needed to provide a set of boundary temperatures for the calculation of detailed temperatures of experiments located on the external surfaces of the LDEF. The THERM experiment provided an economical way for performing a post-flight verification of the TMM by recording a limited number of flight temperatures on selected locations of the LDEF structure.

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The LDEF was deployed on April 7, 1984 into a gravity gradient stabilized posture at a 28½° orbit inclination with near zero rates along the pitch, roll and yaw axes. During the first 390 days of the LDEF mission, the THERM temperature data were recorded on the experiment power and data system (EPDS) recorder which was shared with the Low Temperature Heat Pipe Experiment (exp. S1001). After an LDEF mission of approximately 5¾ years (2105 days), the crew of the orbiter Columbia (STS 32) retrieved the facility from free flight on January 12, 1990 and returned the LDEF to Earth. LDEF altitude at deployment was 255 nm and it had fallen to 180 nm at the time of retrieval. Post-flight analysis indicated the LDEF was yawed 8° to 12° from row 9 towards row 8 throughout the mission, thus biasing the velocity vector towards row 10 (figure 1). Orbital beta angle (figure 2) range for the LDEF mission was ±52°. For the post-flight calculation of temperatures, a new set of orbital detailed heat fluxes were calculated for the beta angle range of ±52° for an average LDEF yaw angle of 10°. A composite daily averaged heat flux table for the first 390 days of the LDEF mission was generated with the new set of orbit detailed heat fluxes and the daily beta angle history. This new set of daily averaged thermal fluxes were used for calculation of daily averaged temperatures which allowed a direct comparison to the recorded THERM flight data.

The external surface thermal properties, absorptivity (α) and emissivity (ε), were measured during the disassembly operations of the LDEF at the Kennedy Space Center (KSC). Measurements were made on exposed and unexposed external structural surfaces, earth and space end thermal panels, tray lips, and a limited number of experiments. The measured α/ε values combined with nominal material specifications were used to formulate the LDEF surface property conditions that existed at the beginning of the mission and the end of the first year (390 days). The preflight TMM was modified by incorporating better estimates of bolted joint conductances, thermal radiation couplings omitted from the original pre-flight model, and better estimates of external surfaces α/ε degradation. The modified TMM was then used to obtain improved calculated flight temperatures for the LDEF spacecraft.

LDEF DESCRIPTION

The LDEF was developed jointly by the Office of Aeronautics And Space Technology (OAST) and Langley Research Center (LaRC) to provide a shuttle launched low cost accommodation for relatively simple experiments. These experiments would require long duration exposure to the space environment (approximately one year). Many experiments were completely passive, depending entirely on post-flight laboratory investigations for the results.

The LDEF is a reusable 12-sided bolted and welded cylindrical structure 14 ft. in diameter and 30 ft. in length (figure 3). Extrusions of 6061-T6 aluminum alloy are the main components for the LDEF structure (intercostals and longerons). The 12-sided cylinder forms a closed cavity when all 72 periphery and 14 end trays are mounted on the exterior of the spacecraft. Each tray can accommodate from one to several different self-contained experiments. The flight configuration for this mission (ref. 1) included 86 trays with a total of 57 experiments for a total weight of over 21,000 pounds.

LDEF THERMAL CHARACTERISTICS

Thermal Design

The thermal control of the LDEF is totally passive, and is accomplished by radiation coupling the inside of the facility, which consists of a hollow polygonal cylinder with closed ends. LDEF's passive thermal control design (ref. 2) maximized the internal radiation coupling between the spacecraft components by using high ε values on the internal surfaces. All interior surfaces are coated with Chemglaze Z-306 flat black paint which has an ε of 0.90. This unexposed coating did not seem to suffer any appreciable deterioration during the 6 year LDEF mission. Internal radiation blockage was decreased by minimizing the number of structural components inside the spacecraft. The cylindrical cavity was closed at all tray locations and at both ends to prevent solar flux from entering the interior. Venting holes were distributed uniformly around the facility. This venting area was approximately 0.15% of total external surface area. The thermal model accounted for the venting holes by coupling an interior dummy node to the space environment.

The bolted construction of the LDEF was a source of uncertainty in the heat conduction across the structural joints. The experiment trays were attached to the LDEF structure by eight 2"× 5" aluminum clamps along the tray perimeter. The tray mounting scheme minimized the contact area through which heat could be transferred between the facility structure and the experiment trays.

All experiments were mounted flush with the outside tray surface, simplifying the thermal modeling of the LDEF. Most tray models were reduced to two nodes (ref. 2) for input into the LDEF TMM. For better heat distribution and reduced temperature difference throughout the spacecraft, more than 50% of the experiment trays were coupled by radiation and conduction between the tray internal and external surfaces. The different panel type trays were uniformly distributed over the surface of the LDEF. Over 50% of the thermal control surface area was provided by the various chromic anodized coatings (figure 4) on the facility's aluminum structure, trays, and debris panels (Space Debris Experiment S0001, 24 trays). The external surface absorptivity to emissivity ratio (α/ε) for each of the tray lips and debris panels varied according to the LDEF thermal design requirements (ref. 3).

LDEF Thermal Model

The programs used for the calculation of the LDEF incident heat fluxes and temperatures were the Thermal Radiation Analysis System II (TRASYS II, ref. 4) and the Systems Improved Numerical Differencing Analyzer (SINDA, ref. 5). The SINDA program was used for the calculation of temperatures. SINDA is a system of computer codes used to solve lumped parameter representations of physical problems governed by diffusion type equations. Parameters include thermal mass, surface properties and thermal conductance. Hand calculated thermal conduction couplings were entered as well as thermal radiation couplings between all surfaces. Most of the internal radiation couplings were computer generated and their number reduced to a manageable size by lumping very small values into a radiation coupling to an internal dummy node. Other detailed radiation couplings between isolated surfaces were generated by hand. LDEF orbital parameters obtained from ground tracking stations were used as input to TRASYS II to calculate the incident thermal solar and infrared heat fluxes. The calculated thermal fluxes were then integrated into the LDEF TMM in order to perform a post-flight temperature analysis.

The original thermal model (ref. 6) was created prior to the LDEF deployment and was restricted by program and computer capabilities to less than 300 nodes. The post-flight TMM size increased to 327 nodes to improve the model's accuracy and facilitate the comparison of selected nodes to the THERM experiment sensor temperatures.

Most experiment trays were described by two nodes (internal and external) with the internal node representing the tray. The external surface of the internal tray node is in the shape of a picture frame. This node was considered isothermal and the experiment was mounted inside it. The more complicated experiments were described by three and four node models. The experiment models were representations of more detailed models that could have as many as 80 nodes before reduction. The reduced node tray/experiment (T/E) models had equivalent energy balance and surface properties to the original T/E detailed models. The temperature values calculated for the T/E nodes represented an average for that tray location. For more detailed values, the T/E detailed thermal model for that location would have to be updated with the boundary temperatures from the LDEF TMM and the component temperatures recalculated using the experiment's detailed thermal model.

The original LDEF TMM was only capable of calculating day/night temperatures for one orbit. As part of the THERM effort a TMM was generated that calculated the daily averaged temperatures of the LDEF. The new model tracked the orbital beta angle (figure 5) instead of the hourly position of the LDEF within the Earth's orbit. This facilitated the direct comparison to the temperatures measured by the THERM system.

Thermal Measurements System (THERM)

The THERM system consisted of five copper-constantan thermocouples (T/C), one suspended radiometer, two thermistor reference measurements, an electronic scanning system, one 7.5-V battery, and an interface harness with the low temperature heat pipe experiment package (HEPP) experiment. The THERM data was recorded on dedicated channels of the shared EPDS tape recorder in the HEPP experiment (ref. 7).

The THERM hardware was located at selected areas of the LDEF interior in order to maximize the thermal environment characterization with a limited number of measurements (figure 6). Two thermistors measured the THERM electronic junction temperatures and were used for system calibration (thermistors #2 and #8). A measurement of the LDEF interior temperature average was made by suspending a radiometer with a T/C at the center of the LDEF interior (T/C #4). The radiometer was coupled radiatively to all of the interior surfaces providing in effect an average of all interior surfaces. T/C #1 was located on the center structure in order to provide a backup temperature value to the radiometer. The center structure is a massive aluminum part that carries the main load of the spacecraft during the deployment and retrieval operations and is coupled radiatively to most of the internal surfaces. T/C #3 was located on top of the magnetic viscous damper thermal radiation shield. This T/C was thermally insulated from the dome and was used to measure the thermal environment around the viscous damper. The temperature measurements taken at this location showed the largest difference from the calculated values. Due to the mounting techniques and the shape of the data response to heat flux changes this measurement is suspect and is the subject of further investigation. The structural temperatures were characterized by the remaining three T/C's. T/C #5 was mounted on a structural member located on row six of the facility. This area was parallel to the orbit plane and experienced incident thermal flux environments that varied widely, depending on the orbital beta angle (β). For β's from 0° to +52° this side of the facility did not see direct solar incident thermal flux (albedo only), while for negative β's, the solar incident occurs for the full day period with orbit β= -52° being the maximum solar exposure for this row. This T/C also provided a good indication of LDEF's in-flight attitude. T/C #6 was located on the space end structure near row 12 to provide space end mounted experiments with representative boundary temperatures. The space end location had the maximum radiative coupling to space and no incident planetary or albedo thermal fluxes. The last temperature measurement, T/C #7, was located on the earth end structure near row six in order to measure the night/day (N/D) temperature cycling on that end with maximum radiative coupling to the planet. Total overall system accuracy was designed to be within ±10°F for all measurements over the range from -30°F to +170°F. The actual recorded temperature range for all seven locations was from a low of 39°F to the maximum of 134°F at the row six location.

DISCUSSION

The THERM data was designed to take a sweep of the thermal sensors with the same sampling rates as the HEPP (S1001) experiment. The fast data rate was designed to record data every five minutes when the low temperature heat pipes achieved cryogenic temperatures, thus providing a detailed orbit temperature profile for direct comparison to the TMM results. The low data rate cycle was designed to record data every 112 minutes and was not dependent on any event to be activated. The HEPP experiment did not reach a low enough temperature to activate the high data rate cycle, recording only at the low data rate and leaving no detailed orbit temperature for comparison to the LDEF thermal model. At the deployment altitude (255 nm), the LDEF orbits the Earth 15.3 times a day, or once every 94 minutes. The period of the recorded data rate for this orbit is approximately equal to six orbits (figure 7). A direct comparison between the measured data and the calculated values was achieved by using the daily averages of the measured temperatures and by modifying the TMM to calculate daily average temperatures as discussed earlier.

After comparing the pre-flight TMM temperatures to the THERM data the areas for improvement became apparent. The modeling of the Earth and space end thermal control panels was improved. The sides of the panels located on the LDEF periphery were not included in the original TMM in order to reduce the number of nodes. In addition, the conduction values across joints were reviewed in order to better account for contact resistance. The resistance to heat transfer across a bolted joint is highly variable and depends on many factors. Empirical values are most commonly used to account for joint conductances. Approximate contact resistance values were calculated by assuming 25% of the actual joint surface contact area. The net effect from this change was to increase the heat flow across some of the joints, while reducing the heat flow across others depending upon the complexity of the joint in question.

The thermo-optical properties of the external surfaces were measured during the LDEF disassembly at KSC and used to modify the TMM (ref. 8). From the coatings assessment it was evident that the coatings on the LDEF had been affected by contamination. Unlike coating degradation, contamination does not have a typical rate of action. The THERM data provided the best estimate for the rate at which contamination affected the external surfaces optical properties. Most of the contamination effects occurred during the first year of flight. The temperature increases could not be accounted for by the orbit β seasonal changes and the materials surfaces typical α/ε rate of change alone. The effects from contamination were added to the estimated α/ε changes due to material degradation from space exposure. The degraded α/ε values used for the surface coatings were those measured during the LDEF disassembly. As the bulk of the outgassing contamination occurred during the beginning of the LDEF mission, it was assumed that the leading edge coatings had the same contamination effects as the trailing edge (Row 3). This assessment is consistent with results from the experiment S0010 (ref. 9). The experiment S0010 included an Experiment Exposure Control Canister (EECC), located on the leading edge of the LDEF. The EECC opened while in orbit at the beginning of the mission and closed prior to the first year of the LDEF flight (as programmed). The opening of the EECC by the principal investigator showed the coatings inside the canister to have contamination similar to that of the trailing edge of the facility, although the post-flight leading edge exposed surfaces' α/ε showed less effects from contamination than those on the trailing edge. The α/ε difference between the leading and trailing edge can be attributed to the cleaning effect occurring on the leading edge surfaces exposed to atomic oxygen impinging flux (AO). The amount of AO rises sharply at lower orbit altitudes and also with increased solar activity such as experienced by the LDEF during the last six months of the mission.

RESULTS

A comparison between the THERM measured temperatures and the TMM calculated values is shown on figures 8 to 14. These curves show the comparison between the calculated and the measured temperature values for all temperature measurement locations. The flight data shown in each plot are the daily average temperatures for that location. Data scans were taken 12 - 13 times a day and the data for each day were averaged into one temperature for that day thus allowing a direct comparison to be made against the thermal model temperature calculations.

A direct comparison of calculated versus measured values was done for each sensor location. The locations with the smallest model error were at the center ring, reference thermistor, and the space end which all had a standard deviation (3σ) of ±9 °F. The earth end and the row six longeron had the next lowest deviation of ±12 °F. The radiometer had the second largest 3σ T/C error of ±15 °F. A maximum uncertainty between the calculated and measured values of ±18°F was obtained at the damper dome location but as stated this T/C is suspect. The curves also show the maximum calculated temperature uncertainties occurred toward the end of the thermal analysis. The LDEF TMM assumed fully degraded α/ε values by the end of the 390 days of the THERM data period. It is likely that the fully degraded surface property values were achieved after the THERM operation, thus the diversion between the calculated and measured temperatures as seen at the end of the data period on all data figures. As the contamination effects on thermal control surfaces properties were highly variable during the course of the first part of the LDEF mission, it was difficult to extrapolate the degradation curve for the affected coatings. A longer operation of the THERM system into the second year of the LDEF mission would have enabled an improved characterization of the contamination effects and a better agreement between the calculated and measured temperatures towards the end of the data period. The 3σ uncertainties (Table 1) are no greater than ±18°F for any of the THERM temperature sensor locations, thus achieving the desired reduction of calculated temperature uncertainties to under ±20°F. Given in Table 2 are the temperature range comparisons between the design limits, measured temperatures, and the post-flight calculated temperatures for the T/C locations.

CONCLUSION

The post-flight calculation of the LDEF flight temperatures have been achieved with an uncertainty of under ±20°F even with the use of fully degraded surface values at the end of the temperature data period. The LDEF facility design temperatures were maintained throughout the mission. The thermal control contamination made the extrapolation of the surface coatings degradation into the second year very difficult due to the lack of temperature data. The calculated temperatures would show a better agreement if the THERM data had been available for the full period of the surface degradation driven by contamination. The TMM assumed fully degraded thermal coatings thermo-optical properties towards the end of the data period.

The reduction of calculated space exposure temperature uncertainties with post-flight data proved to be feasible for spacecraft of the LDEF type. The use of this method for reducing uncertainties of calculated values was necessary due to the lack of pre-flight model verification. Second and following flights of this multi-flight spacecraft would benefit even more from this approach by using results from the previous mission for better pre-flight temperature predictions.

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TABLE 1 CALCULATED THERMAL MODEL UNCERTAINTY

MEASUREMENT LOCATION	UNCERTAINTY (± °F) 1σ	UNCERTAINTY (± °F) 3σ
THERMISTOR	3	9
RADIOMETER	5	15
CENTER RING	3	9
ROW 6 LONGERON	4	12
EARTH END STRUCTURE	4	12
SPACE END STRUCTURE	3	9
DAMPER DOME	6	18

TABLE 2 COMPARISON OF LDEF TEMPERATURE RANGES

LDEF LOCATION	TEMPERATURE DESIGN LIMITS °F	MEASURED (THERM) °F	POST FLIGHT CALCULATED °F
INTERIOR AVERAGE	10 - 120	52 - 89	58 - 89
STRUCTURE NORTH/SOUTH (ROWS 6/12)	-10 - 150	35 - 134	39 - 136
STRUCTURE EAST/WEST (ROWS 3/9)	-10 - 150	N/A	53 - 100
STRUCTURE EARTH END	10 - 135	56 - 103	57 - 104
STRUCTURE SPACE END	10 - 135	60 - 90	64 - 96

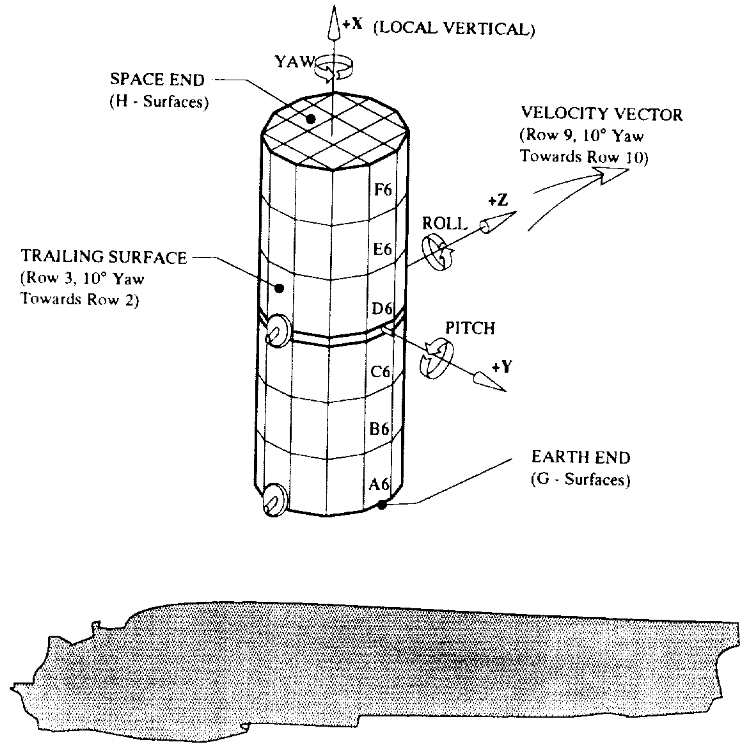
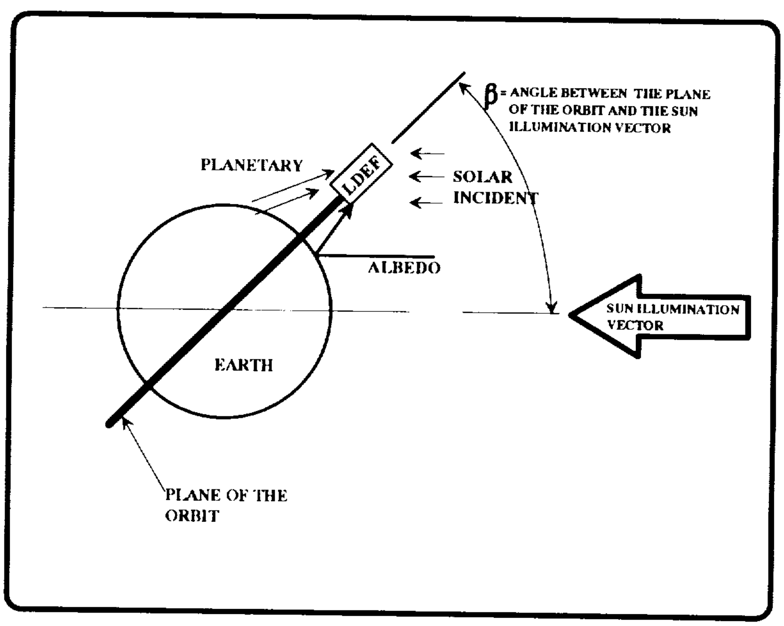


Figure 1. LDEF in Free Flight.



BETA ANGLE= (β) Angle between the plane of the orbit and the sun illumination vector.
SOLAR INCIDENT= (BTU/Hr-Ft^2) Heat due to direct illumination from the sun.
ALBEDO= (BTU/Hr-Ft^2) Heat due to the portion of the solar incident energy reflected from the planet into the LDEF.
PLANETARY= (BTU/Hr-Ft^2) Heat due to energy emitted from the planet.

Figure 2. LDEF Beta Angle Definition.

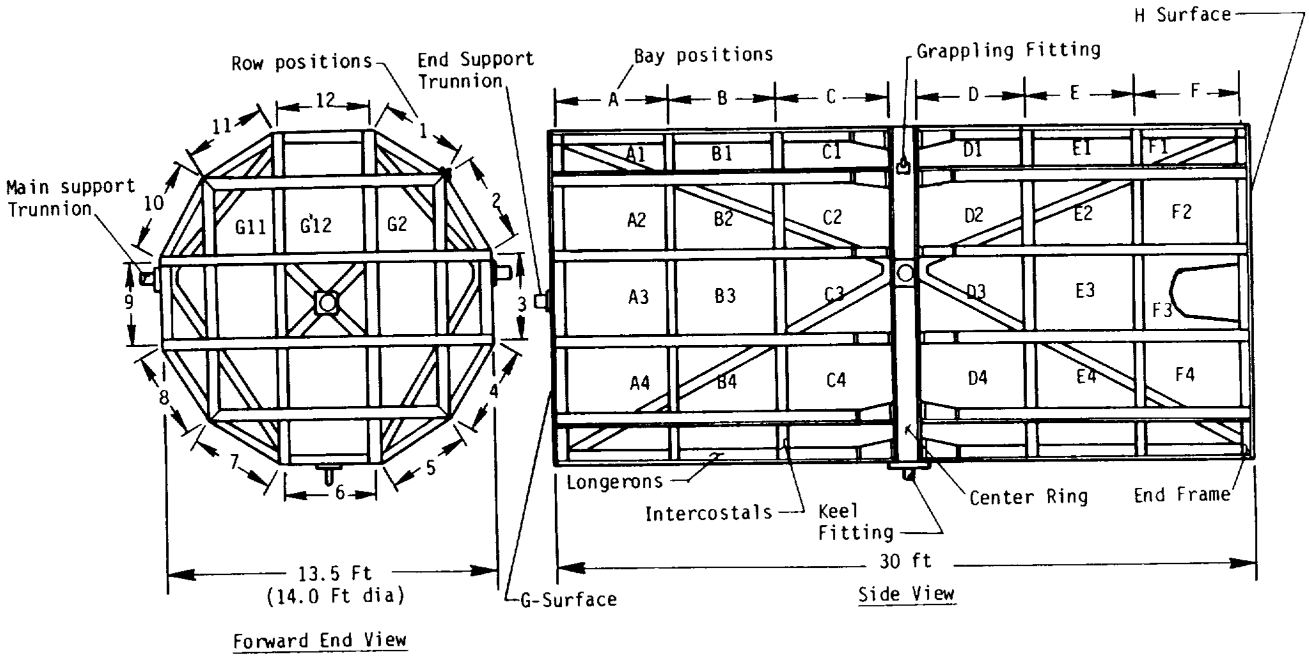


Figure 3. LDEF Structure.

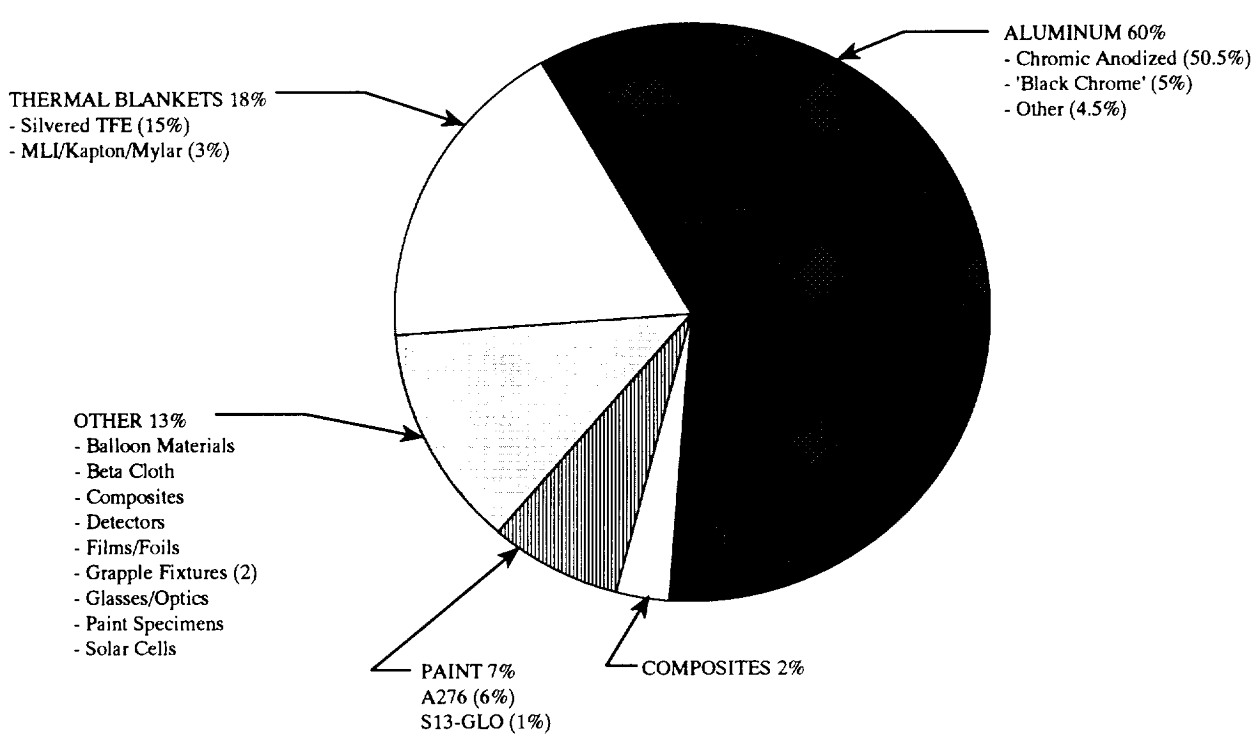


Figure 4. LDEF External Surface Coating Distribution.

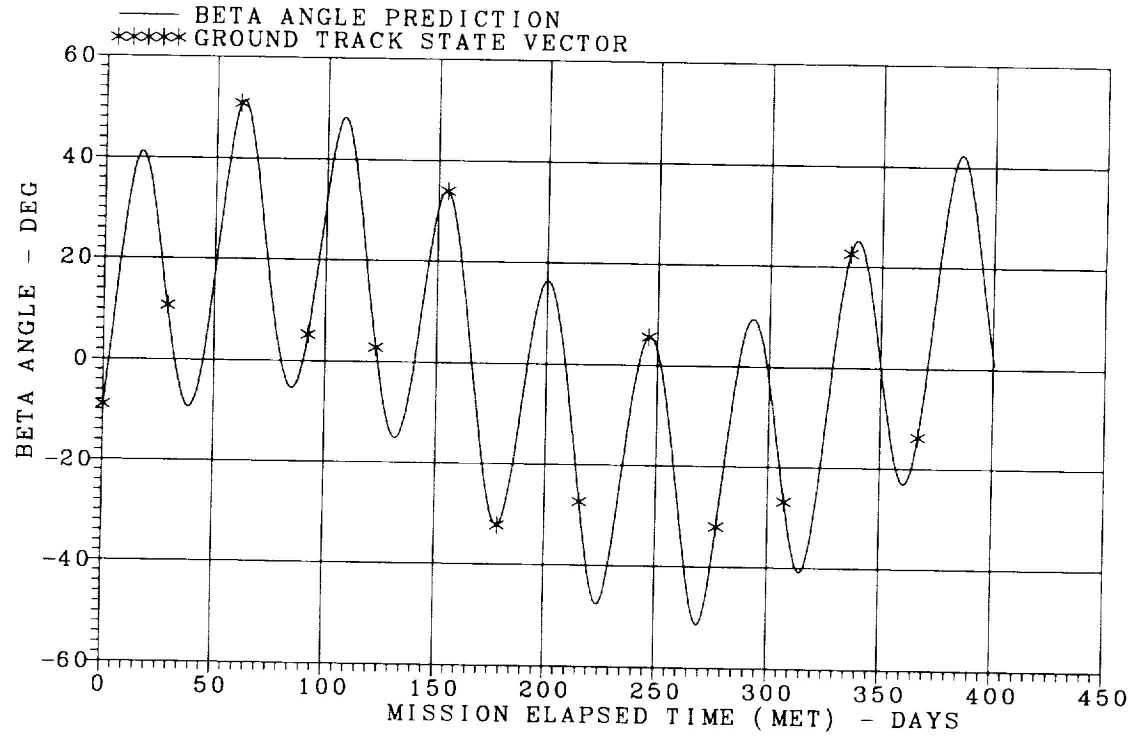


Figure 5. LDEF Beta Angle; April 7, 1984 - May 13, 1985.

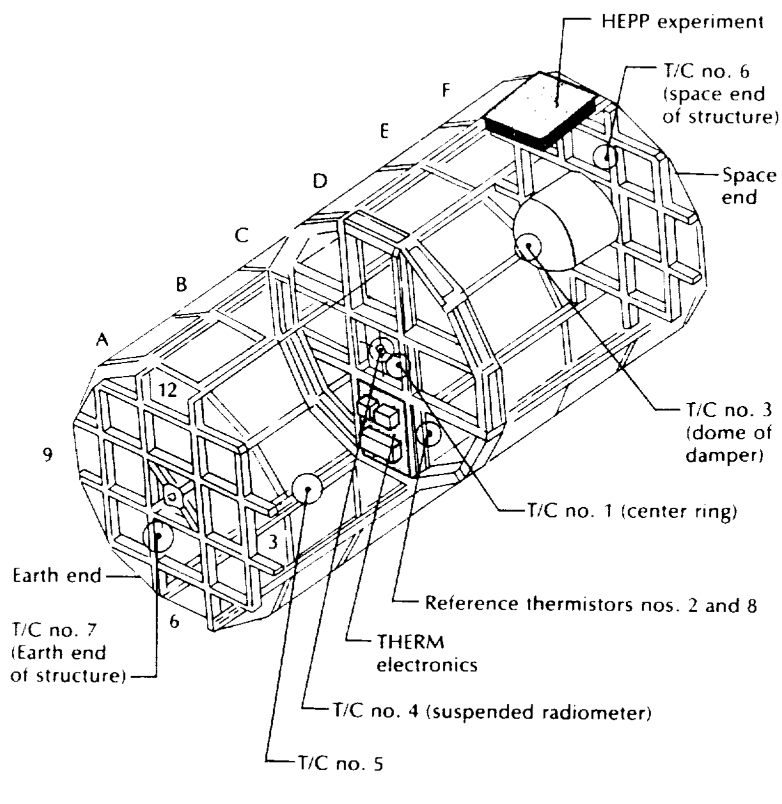
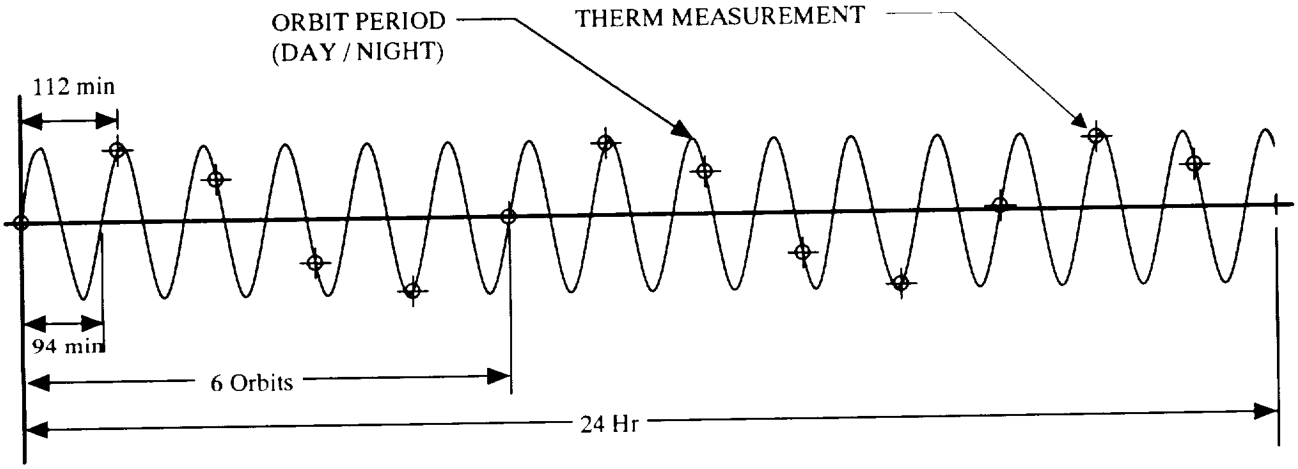


Figure 6. Location of THERM Hardware on LDEF.



MISSION MEASUREMENTS PER LOCATION: 4983

TOTAL DAYS: 390

Figure 7. LDEF THERM Data Measurement Cycle.

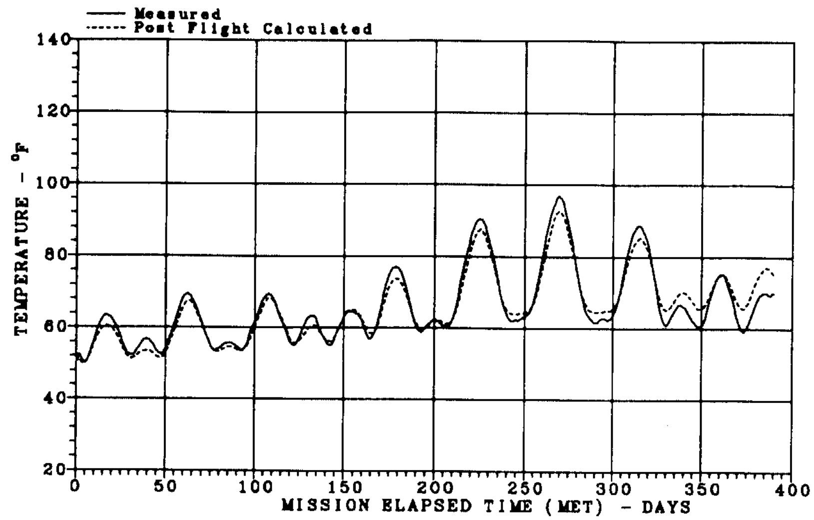


Figure 8. THERM Thermistor Data vs LDEF Post Flight Thermal Model.

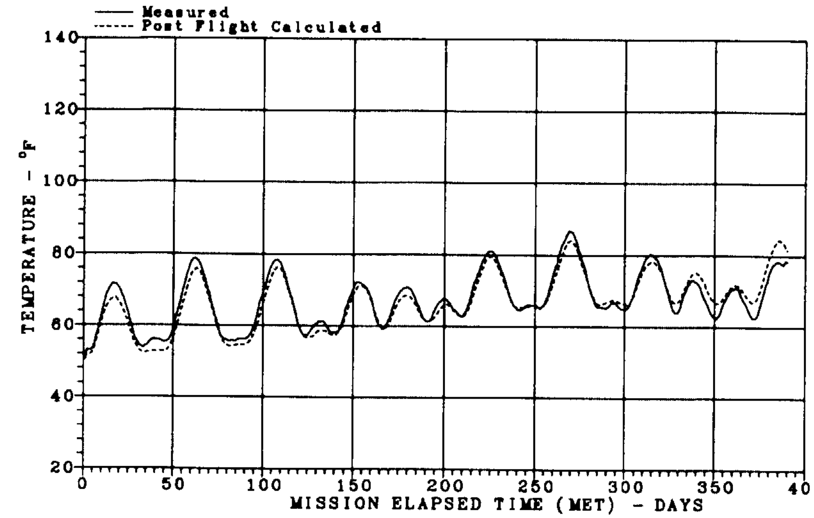


Figure 10. THERM Center Ring Data vs LDEF Post Flight Thermal Model.

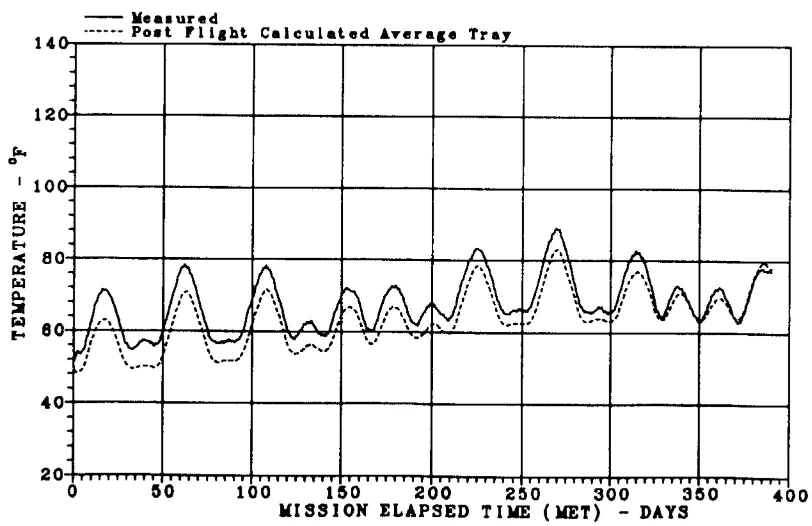


Figure 9. THERM Radiometer Data vs LDEF Post Flight Thermal Model.

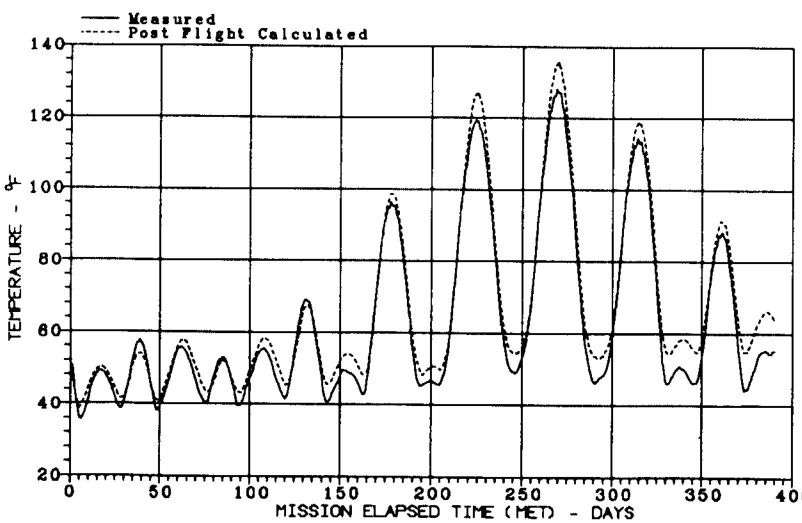


Figure 11. THERM Row 6 Longeron Data vs LDEF Post Flight Thermal Model.

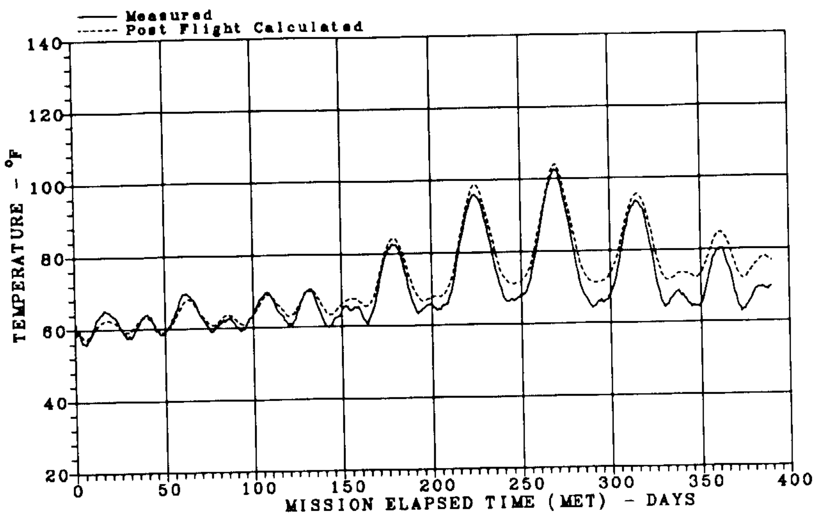


Figure 12. THERM Earth End Data vs LDEF Post Flight Thermal Model.

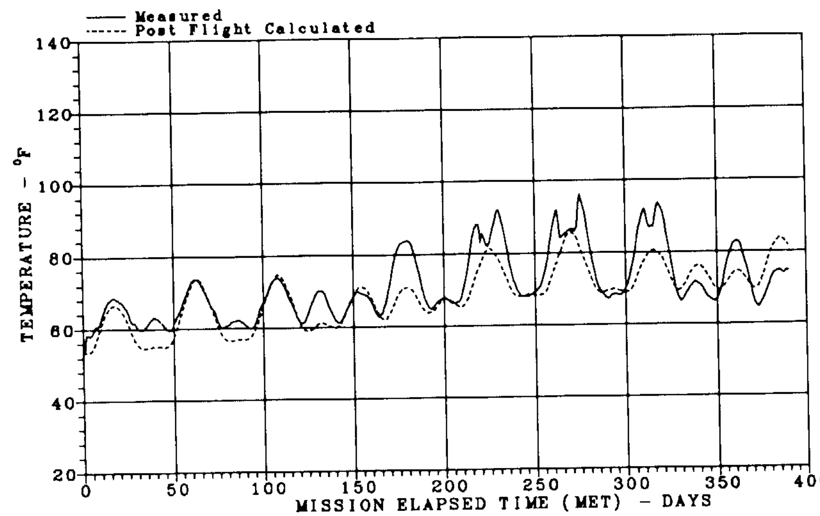


Figure 14. THERM Damper Dome Data vs LDEF Post Flight Thermal Model.

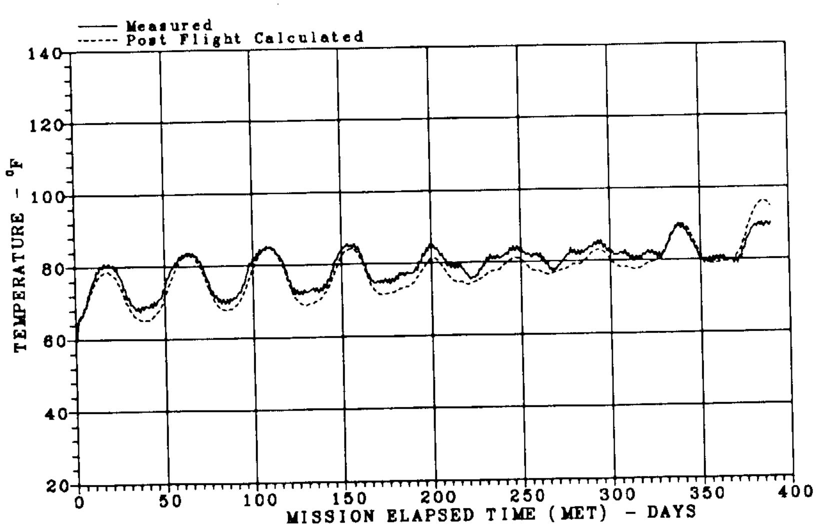


Figure 13. THERM Space End Data vs LDEF Post Flight Thermal Model.